

**Final Report: NASA Grant Number NAG5-3439**

**Monitoring Change in Temperate Coniferous Forest Ecosystems**

Principal Investigator: Curtis E. Woodcock  
Department of Geography  
Boston University  
675 Commonwealth Avenue  
Boston, MA 02215

Copies Submitted to:

NASA Technical Officer: Darrel Williams

NASA's Goddard Space Flight Center  
Mail Stop 923.0  
Greenbelt, Maryland 20771-0001

NASA Grant Officer: Sandra Russo  
NASA's Goddard Space Flight Center  
Mail Stop 923.0  
Greenbelt, Maryland 20771-0001

NASA Center for AeroSpace Information (CASI)  
Attn: Document Processing Section  
7121 Standard Drive  
Hanover, MD 21076

ONR Contract Specialist: Eric Garfield,  
ONR Boston Regional Office  
495 Summer Street, Room 623  
Boston, MA, 02210-2109

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## **Abstract and Introduction**

The primary goal of this research was to improve monitoring of temperate forest change using remote sensing. In this context, change includes both clearing of forest due to effects such as fire, logging, or land conversion and forest growth and succession. The Landsat 7 ETM+ proved an extremely valuable research tool in this domain. The Landsat 7 program has generated an extremely valuable transformation in the land remote sensing community by making high quality images available for relatively low cost. In addition, the tremendous improvements in the acquisition strategy greatly improved the overall availability of remote sensing images. I believe that from an historical perspective, the Landsat 7 mission will be considered extremely important as the improved image availability will stimulate the use of multitemporal imagery at resolutions useful for local to regional mapping. Also, Landsat 7 has opened the way to global applications of remote sensing at spatial scales where important surface processes and change can be directly monitored. It has been a wonderful experience to have participated on the Landsat 7 Science Team.

The research conducted under this project led to contributions in four general domains:

- I. Improved understanding of the information content of images as a function of spatial resolution;
- II. Monitoring Forest Change and Succession;
- III. Development and Integration of Advanced Analysis Methods;
- IV. General support of the remote sensing of forests and environmental change.

This report is organized according to these topics. This report does not attempt to provide the complete details of the research conducted with support from this grant. That level of detail is provided in the 16 peer reviewed journal articles, 7 book chapters and

5 conference proceedings papers published as part of this grant. This report attempts to explain how the various publications fit together to improve our understanding of how forests are changing and how to monitor forest change with remote sensing.

There were no new inventions that resulted from this grant.

## **I. Improved understanding of the information content of images as a function of spatial resolution**

The fundamental strength of remote sensing as a measurement strategy is the ability to repeatedly capture landscape heterogeneity and provide extensive areal coverage. However, these objectives compete for sensing resources, as it is not possible to provide global coverage at fine spatial resolutions with high frequency. Thus, fundamental to sensing design are questions of optimum spatial resolutions. Beyond the issues in the logistics of sensor design, this question is difficult because the answer varies as a function of many variables, including some related to the landscapes in question and the intended uses of the imagery. To date, there has not been a sound, objective way to evaluate spatial resolution requirements that takes the nature of intended uses of the imagery into consideration. Work done as part of this project has developed a way of evaluating quantitatively the tradeoffs between spatial resolution and information content of images that is application specific. The key to the proposed approach is the ability to separate the effects in images associated with different landscape scales. The theory behind the methods is presented in Collins and Woodcock (2000) based on hierarchical decomposition of variograms. In essence, the methods developed allow for evaluation of the effect of spatial resolution (or regularization) on the information content of images (or variance) for different landscape scales. This method served as the basis for development of methods to estimate the variance of resolution-dependent images in an analytical way (Collins and Woodcock, 1999a). The paper demonstrating this approach and illustrating its value for under-

standing the effect of changes in spatial resolution on images won the **2000 Autometric Award** for the Best Paper in Photogrammetric Interpretation, from the *American Society of Photogrammetry and Remote Sensing*.

One way the methods above can be used is for evaluating the utility of thresholds for detecting phenomena in images as a function of spatial resolution. Collins and Woodcock (1999b) demonstrate this process for mapping snow cover using Landsat TM imagery. Included in this book chapter is the theory required for evaluating various thresholds as a function of the resolution of imagery, as well as a practical example.

Another way that the above methods can be used is to evaluate the utility of thresholds for detecting change in multirate images as a function of the spatial resolution of the imagery. Thresholding of difference images is a common method of change detection and this was demonstrated in the dissertation of John Collins, a PhD student supported on this grant.

### **References in Support of Section I**

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## **II. Monitoring Forest Change and Succession**

At the heart of the research conducted for this grant is the question of how to monitor changes in forests over time using remote sensing. In this context it is important to monitor both forest clearing and forest growth (or succession). The two kinds of changes are quite different in nature as forest clearing (due to harvest, fire, development or other causes) happens quickly and is a dramatic change. On the other hand, forest growth is slow and gradual and constitutes very minor changes over short periods of time. Hence the two kinds of change required very different approaches.

### **Monitoring Forest Clearing.**

Many factors can lead to the clearing of forests in the temperate zone, including timber harvest, fires, and conversion of land to other uses such as farming or urbanization. Forest clearing can be monitored using "endpoints" imagery, as has been demonstrated for local applications for many years. The key to our research was to develop methods that could be used over large areas to quickly monitor forest clearing. We successfully demonstrated the ability to generalize across time periods, within regions and across Landsat sensors using methods based on artificial neural networks and image segmentation (Woodcock et al., 2001). One finding of this work was the importance of the atmospheric correction process.

## **Monitoring Succession.**

Monitoring of forest age, or successional stage has proven difficult using remote sensing. Spectral indices were not reliable indicators of stand age. In an attempt to understand how the spectral reflectance of stands change through time as the stand matures and grows, we adopted a modeling approach. By using the output from a forest growth model (ZELIG) as the input to a forest canopy reflectance model (GORT) we were able to predict the way the spectral reflectance would change through time for a forest stand. The results were extremely revealing. The spectral/temporal trajectories of stands were highly nonlinear, which helped explain why past methods based on spectral indices had limited success (Song et al., 2002 and Song and Woodcock, 2003). Using a similar approach but focussing on the spatial properties of stands as they grow and mature, we demonstrated the value of using multiresolution imagery to monitor stand age (Song et al., 2002b and 2003b). The spatial variance of stands change through time in ways that are diagnostic of stand age. The spatial variance of images decreases more rapidly as resolution becomes coarser for stands with small trees (or young stands). We were able to develop the theory for this approach and demonstrate it for stands in the H.J. Andrews Experimental Forest in Oregon.

The ability to monitor succession and forest stand age is important as land use history and the resulting age distribution of stands in a region has significant implications for terrestrial carbon budgets (Song and Woodcock, 2003). Following establishment, forest stands increase as a sink of carbon quite rapidly and then as they accumulate more biomass begin to decrease in the rate they absorb carbon. Our results indicate that old growth stands eventually become carbon neutral and maintain a biomass somewhat less than the peak biomass. This result combined with the land use history (harvest rates) in the Pacific Northwest indicate that the current age distribution of

stands includes large amounts of forest in the carbon accumulation stage. This sink of carbon is enough to offset losses of carbon due to harvesting. Even if harvesting continues at current rates, this region will remain a sink for decades to come.

## References in Support of Section II

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### **III. Development and Integration of Advanced Analysis Methods**

The efforts to monitor forest change and succession described above were supported and made possible by a number of developments in methods and models. The two primary developments in this domain were the integration of the use of neural networks in image analysis and the development, refinement and application of the use of a Geometric Optical Radiative Transfer (GORT) model for the interaction of sunlight with plant canopies.

#### **The Use of Neural Networks in Remote Sensing.**

Efforts to understand and model the way the human brain works have proven valuable for a wide range of data analysis purposes. Over the course of this project we did a considerable amount of work on the problem of how to adapt and apply neural networks in the analysis of satellite imagery. Also, the use of neural networks was a significant component of the forest change monitoring scheme we developed, as mentioned above (Woodcock et al., 2001).

Our work on neural networks involves both significant methodological developments and adaptations for applications in remote sensing and demonstration of the use of neural networks for a variety of applications. The Fuzzy ARTMAP neural network was the focus of our work, and we derived significant benefit from access to the



original developers (in particular, Dr. Gail Carpenter) of the neural network at Boston University. Also deserving particular mention is Professor Suchi Gopal, a leading expert in the integration of neural networks in many geospatial analysis domains.

One early application of neural nets for change detection involved monitoring the extent of forest mortality due to drought in the Sierra Nevada Mountains of California (Gopal et al., 1998). This effort was followed by a demonstration of the use of neural networks for mapping global land cover (Gopal et al., 1999). Later topics included applications of neural networks for mixture analysis (Carpenter et al., 1999a) and improved methods of image classification that integrate ancillary data sources (Carpenter et al., 1999b).

#### **Development and Application of the GORT model.**

Of great importance to the effort described above for monitoring forest succession was the continued development of the GORT model. It was originally developed by Dr. Xiaowen Li, but for use for applications such as succession modeling it had to be further developed and modified, as was done in (Ni et al., 1999a and 1999b). The tremendous benefit of the GORT model for the work by Song et al. above (Song and Woodcock, 2002 and 2003a+b; Song et al., 2002) lies in the ability to estimate the directional reflectance of a forest stand as a function of its structure. Thus, it was possible to estimate both directional effects from a single stand and the effect of changing stand structure through time, or succession, on canopy reflectance.

#### **References for Section III**

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#### **IV. General efforts in support of the remote sensing of forests and environmental change.**

In addition to the above activities, my participation on the Landsat Science Team afforded me the opportunity to do a number of things that could best be characterized as *general efforts in support of remote sensing of forests and environmental change*. Among these efforts are a number of book chapters and research on topics of importance to this project as well as many others in remote sensing. For example, as part of my effort for the Landsat Science Team, I became aware of the importance and central role of atmospheric correction for the global science mission of Landsat. Thus, we pursued this topic and developed some general guidelines for when and how to apply atmospheric correction (Song et al., 2001). The importance of atmospheric correction for monitoring change over large areas is highlighted in Woodcock et al., 2001). I was also fortunate to be able to contribute to chapters for a number of books that help promote the value of remote sensing for mapping and monitoring vegetation.

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## **Conclusions**

There are a number of significant conclusions that arise from the work conducted as part of the research supported by this grant. Among them are the following:

- 1). It is possible to generalize mapping and change monitoring algorithms across space, time and Landsat sensors. This finding makes it possible to begin to design mapping and monitoring efforts at the high spatial resolution of Landsat over very large areas in support of the global science mission of Landsat.
- 2). Monitoring forest clearing with Landsat data can be done with very high accuracy and relatively minor levels of effort.
- 3). Succession in forest stands in the Pacific Northwest results in highly nonlinear changes in reflectance, helping explain why it has been so difficult to recover stand age from conventional vegetation indices.
- 4). The role of forests in the Pacific Northwest in the regional carbon budget is strongly influenced by land use history and the resulting age distribution of forest stands.
- 5). The forests of the Pacific Northwest have been carbon sources for most of the 20th century and are now becoming carbon sinks and will continue to be carbon sinks if harvesting continues at present levels.
- 6). Combining geostatistics and hierarchical schemes for landscape organization yields powerful methods for evaluating the information content of images as a function of spatial resolution for different landscape features.

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